VERY HIGH ENERGY OBSERVATIONS OF PSR B1951+32

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ABSTRACT

PSR B1951+32 is a γ-ray pulsar detected by the *Energetic Gamma Ray Experiment Telescope* (EGRET) and identified with the 39.5 ms radio pulsar in the supernova remnant CTB 80. The EGRET data shows no evidence for a spectral turnover. Here we report on the first observations of PSR B1951+32 beyond 30 GeV. The observations were carried out with the 10m γ-ray telescope at the Whipple Observatory on Mt. Hopkins, Arizona. In 8.1 hours of observation we find no evidence for steady or periodic emission from PSR B1951+32 above $\sim$ 260 GeV. FLux upper limits are derived and compared with model extrapolations from lower energies and the predictions of emission models.

INTRODUCTION

The pursuit of Very High Energy (VHE) astrophysics has resulted in the discovery of five sources, of which three are associated with young spin-powered pulsars. VHE emission has been detected from the direction of the Crab Nebula (Vacanti et.al., 1991), the Vela pulsar (Takanori 1996) and PSR B1706-44 (Kifune et al., 1995) but no evidence has been found for periodic emission at these energies in these experiments.

PSR B1951+32 has been detected as a pulsating X-ray source (Safi-Harb et al., 1995) and as a high energy γ-ray pulsar at E $\geq$ 100 MeV at the radio period (Ramanamurthy et al., 1995). It can be inferred from the five pulsars seen in the MeV to GeV γ-ray region that longer period or older ($\sim 10^5$ years) pulsars have a greater fraction of spin down energy emitted as high energy γ-rays. The best fit outer gap model of Zhang and Cheng (1997) suggests that PSR B1951+32 should emit detectable levels of TeV γ-rays (Figure 2). The multiwavelength spectrum of PSR B1951+32 (Figure 1b) indicates a maximum power per decade at energies consistent with a few GeV and still rising at 10 GeV. These factors make PSR B1951+32 a good candidate for observations with the ACT above 100 GeV.

OBSERVATIONS

The observations of PSR B1951+32 reported here were acquired with the 10m reflector located at the Whipple Observatory on Mt. Hopkins in Arizona. A total of 14 *Tracking* runs and 4 *On/Off* pairs taken between 13th May, 1996 and 17th July, 1996 constitute the database for all subsequent discussion. The total *On* source observing time is 8.1 hrs. The radio position (J2000) of PSR B1951+32 ($\alpha = 19^h\ 52^m\ 58.25^s$, $\delta = 32^\circ\ 52'\ 40.9''$) was assumed for the subsequent timing analysis.

PSR	P msec	$\dot{P}$ $10^{-15}ss^{-1}$	Distance kpc	$\log_{10}$B Gauss	$\mathrm{Log}_{10}\dot{E}$ ergs/s
B1951+32	39.53	5.8494	2.5	11.69	36.57

ANALYSIS AND RESULTS

Standard Analysis

The event selection criteria are collectively called *Supercuts95* and a detailed description can be found elsewhere (Catanese et al., 1995). *Supercuts95* raises the effective energy threshold of the detector with its software trigger and *size* cuts. PSR B1951+32 appears to have a steep spectrum at EGRET energies and since the pulsar spectrum is expected to cut off, it behooves us to reduce the threshold of our analysis to search for a lower energy signal. The dominant background at lower energies is due to muons whose images appear in the camera as arcs and can be discriminated by a cut on their large *length*/*size* values. Hence the selection criteria used *Supercuts95* on images with sizes larger than 400 p.e. and *Smallcuts* (Table 2) for images with sizes less than 400 p.e. No steady emission is

Table 2: Parameter ranges for selecting γ-ray images

Parameter	Supercuts95	Smallcuts
length	0°16 - 0°30	unchanged
width	0°073 - 0°15	unchanged
distance	0°51 - 1°1	unchanged
alpha	$< 15^{\circ}$	unchanged
max1	$>$ 100 p.e.	45 p.e. - 100 p.e.
max2	$>$ 80 p.e.	45 p.e. - 80 p.e.
size	$\geq$ 400 p.e.	0 - 400 p.e.
length/size	not used	$< 7.5 \times 10^{-4}$ °/p.e.

Table 3: Selected Events for Steady Emission analysis

Selection	Source Events $\alpha < 15^{\circ}$	Background Events $\alpha < 15^{\circ}$	Excess	Significance
Supercuts95	292	254	38	1.16σ
Smallcuts	618	672	-54	-1.10σ
Supercuts95 + Smallcuts	910	926	-16	-0.24σ

detected from PSR B1951+32 and 3σ flux upper limits are displayed in Table 4. The effective area for *Supercuts95*, that was used to calculate the upper limit, was taken as $A_{eff} \sim 3.5 \times 10^8$ cm^2: the same area was used for the dataset that resulted from a combination of *Supercuts95* and *Smallcuts* although here there is more systematic uncertainty. The energy threshold was obtained from simulations and extrapolating the Crab Nebula γ-ray rate for each set of cuts used assuming a spectrum $\sim E^{-2.4}$.

Periodic Analysis

The arrival times of the Čerenkov events were registered by a GPS clock with an absolute resolution of 250 μsec. An oscillator calibrated by GPS second marks was used to interpolate to a resolution of

system barycenter and folded to produce the phases, ϕ_j, of the events modulo the pulse period. The ephemeris frequency parameters used were ν= 25.2963719901267 s^{-1} and $\dot{\nu}$=-3.73940$\times 10^{-12} s^{-2}$, at the epoch t_0=JD 2450177.5. This frequency was extrapolated 72 days to obtain a timing solution relevant to the epoch of observation. The datasets, however, were taken within the validity interval of the above ephemeris.

To check the Whipple Observatory timing systems an *optical* observation of the Crab pulsar was undertaken on December 2nd (UT) 1996 using the 10m reflector. The phase analysis of the event arrival times yielded a clear detection of optical Crab pulsar signal which is in phase with the radio pulse and demonstrates the validity of the timing, data acquisition and software in the presence of a pulsed signal. No evidence of pulsed emission from PSR B1951+32 at the radio period exists. To calculate a pulsed flux upper limit we assumed the same pulse profile as seen at EGRET energies, i.e. with the phase range for the main pulse and secondary pulse as 0.12 - 0.22 and 0.48 - 0.74 respectively (Ramanamurthy et al., 1995).

Table 4: Integral Flux Upper limits

	Steady Emission cm^{-2}s^{-1})	Periodic Emission (cm^{-2}s^{-1})	Threshold (GeV)
Supercuts95	0.97×10^{-11}	3.7×10^{-12}	≥ 370
Supercuts95 + Smallcuts	1.95×10^{-11}	6.7×10^{-12}	≥ 260

DISCUSSION

PSR B1951+32 is surrounded by a compact nebula which gives a plerionic nature to the supernova remnant, CTB80. X-ray plerions are good candidates for VHE emission since the electrons responsible for nebular synchrotron X-rays should also create VHE γ-rays via the inverse Compton (IC) process. It is expected that for plerions, such as that associated with PSR B1951+32 where the density of nebular synchrotron photons is too low for SSC to take place, detectable VHE emission should be produced by the IC scattering of the 2.7K cosmic microwave background by the same electrons radiating synchrotron X-ray photons. Interpreting the unpulsed X-ray emission form CTB80 as the synchrotron emission from a plerion, the estimated IC flux > 1 TeV is 6.6×10^{-13} TeV/cm^2/s/TeV (De Jager et. al., 1995). This represents the lower limit on the IC flux since there can be other sources of soft photons in addition to the microwave background.

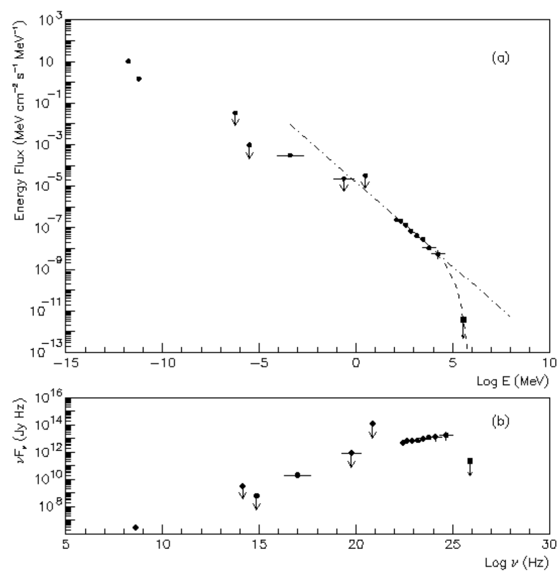

Fig. 1: The pulsed energy spectrum of PSR B1951+32. The Whipple limit is indicated as a filled square at 370 GeV. (See text for details).

To model the pulsed high energy spectrum, a function of the form

$$dN_\gamma/dE = KE^{-\Gamma}e^{(-E/E_0)} \quad (1)$$

was used where E is the photon energy, Γ is the photon spectral index and E_0 is the cut off energy. The pulsed upper limit reported here is two orders of magnitude lower than the extrapolated EGRET power law. Equation (2) was used to extrapolate the EGRET spectrum to VHE energies constrained

emission (Figure 1a).

The strength of the cut off provides a good discriminant between the various pulsar emission models. The status of current observations and the derived cutoff discussed above indicates that the cutoff is beyond 10 GeV. In polar cap models this would indicate a sharp cutoff since the pair production optical depth increases exponentially with photon energy (Harding 1997). However, it is not possible to constrain the shape of the cut off with the non detection of pulsed TeV flux reported here. The most relavant comparison of the Whipple upper limit with emission models is the outer gap model of Zhang and Cheng (see Figure 2). This model includes the effect of geometry in the treatment of pulsed emission via a parameter $\alpha = r/r_L$, the radial distance to the synchrotron emitting region near the outer gap, r, as a function of the light cylinder radius r_L. Our pulsed upper limits are consistent with the outer gap model if $\alpha > 0.6$ implying an emission region far out in the magnetosphere.

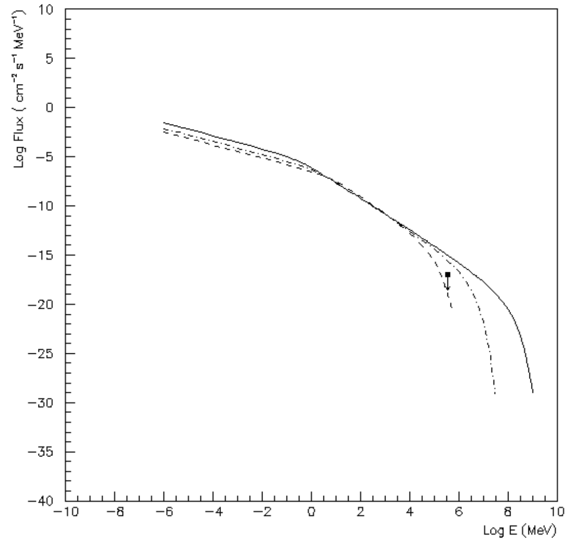

Fig. 2: Predicted pulsed γ-ray flux of PSR B1951+32 from the Zhang and Cheng outer-gap model. The solid, dot-dash and dashed curves correspond to α=0.5, 0.6, 0.7 respectively. (See text for details).

The result reported here is the first observation of PSR B1951+32 beyond 30 GeV. PSR B1951+32 exhibits very similar spectral behavior and morphological features, such as an associated synchrotron nebula, to PSR B1706-44 (Finley et al., 1997). If these factors are any indication of similar emission mechanisms in pulsars then the lack of unpulsed emission from PSR B1951+32 is puzzling considering that PSR B1706-44 was detected as a VHE source of unpulsed emission > 1 TeV (Kifune et al., 1995). Lack of pulsed emission indicates that the processes producing pulsed high energy photons over two decades of energy in the EGRET energy range somehow become ineffective over a decade of energy to result in a lack of VHE γ-rays. The low magnetic field of PSR B1951+32 relative to the average pulsar field implies that attenuation of γ-rays by magnetic absorption is not a likely explanation for the non-detection.

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